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Analysis of Neutral Ground Resistance Behavior of Fourth Refinery Gas Power Plant in Real Short Circuit Faults

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***Abstract* – The Fourth Refinery is one of the largest refineries in Iran due to its vast area as well as its extensive equipment. This refinery includes three gas phases consisting of six operational trains. The vastness of this refinery combined with its involved processes as well as equipment frequency and complexity make it stand out among other refineries, so much so that every minute a train has to be turned off would lead to irreparable and heavy financial losses. The neutral points of the 11kV/33kV transformers supplying electricity to The Fourth Refinery are earth-connected through NGRs (neutral ground resistors). The transformer NGRs are equipped with tap changers which are damaged and burned without the utilizer's knowledge in the event of a short circuit. Therefore, any kind of short circuit in the power system of The Fourth Refinery would damage the protective NGRs and CTs, thus destroying the system protection units, which might in turn lead to tripping of the refinery as a whole. For this reason, an attempt was made in the present article to solve this problem by conducting simultaneous theoretical calculations, simulations, and practical tests.**

***Keywords* – Charging Current, Fourth Refinery Gas Power Plant, Neutral Grounding Resistors, Practical Tests, Single Phase To Ground Short Circuit, Simulation in MATLAB.**

I. INTRODUCTION

The Fourth Refinery has a capacity of 120 MW supplied via four 30.06 MW generators. The required 11 kV voltage for each generator is provided by a 11kV/33kV transformer. In addition, as a backup power supply, Mobin Power Plant has been synchronized with The Fourth Refinery. The transformers operate via Dyn11 connections. The neutral point of each transformer is grounded via a ground resistance. Fig. 1 shows the single-line view of the gas plant and the fourth refinery.

Both high voltage levels (33kV, 11kV, and 6kV) and low voltage levels (110V, 220V, 400V, etc.) are required in The Fourth Refinery. The most frequent electrical fault occurring in this refinery is the single line to ground fault (LG) at the 33kV voltage level.

According to the fault reports, each single-phase short circuit to the ground causes the transformer's NGRs to burn. The resulting isolation of the transformer's neutral from the ground can expose the system to severe over voltage (6 to 8 times the rated voltage). Location of the fault often involves numerous problems. Grounding is accompanied with electrical sparks which are highly dangerous to the personnel and the equipment alike[1].

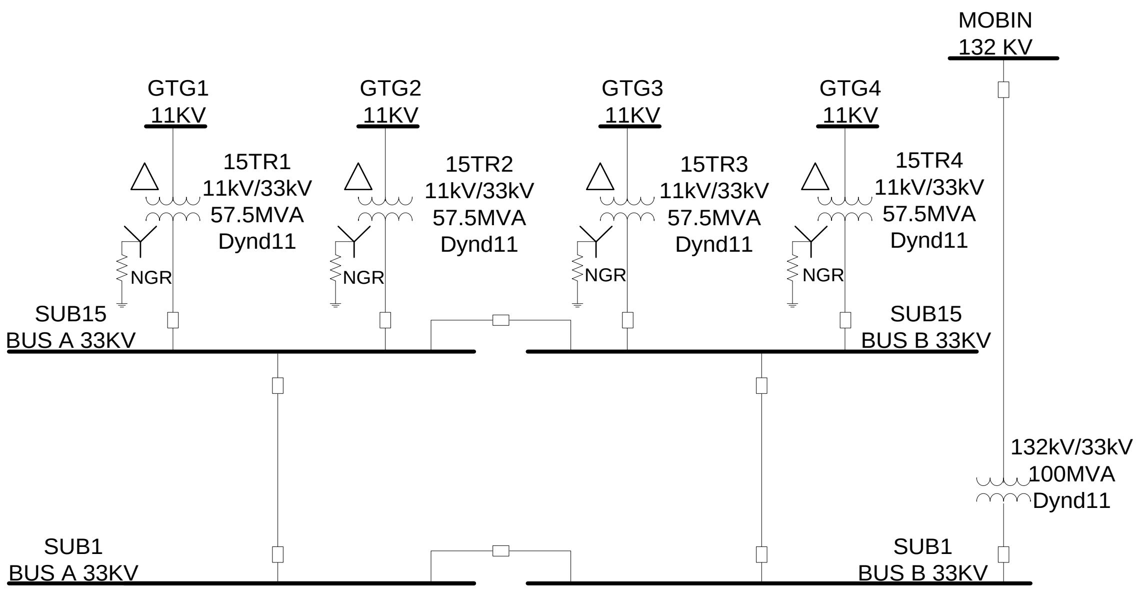

Fig. 1: The single-line view of the gas plant and the fourth refinery

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II. Description of the NGRs

Each NGR consists of four stages designated with numbers 1, 2, 3, and 4. Stage 1 comprises 40 resistance elements in two parts (20 in each part) connected in series. Stages 2, 3, and 4 also have 54 resistance elements in two parts (each part comprising 27 resistance elements) connected in series. As shown in Fig. 2, Stage 1 has a 15.75 ohm resistor and Stages 2-4 have 42.3 ohm resistors. Each resistance element comprises 51 ribbon resistors connected via spot welding. The ribbon resistors are held by two metal rods and the ribbons are isolated from one another and from the rods through small insulators. The NGRs have two 127 ohm/200 A and 47.6 ohm/400 A taps. Fig. 3 shows the tap connection configurations.

III. Description of the Accidents

A. Single Phase to Ground Short Circuit at Input to Station No. 8

This accident happened on Dec. 31, 2010. The refinery was operating normally before the accident. Mobin Power Plant and Turbine Generator No. 1 (synchronously connected) jointly supplied power to the refinery. The power consumption at the time of the accident was 23 MW.

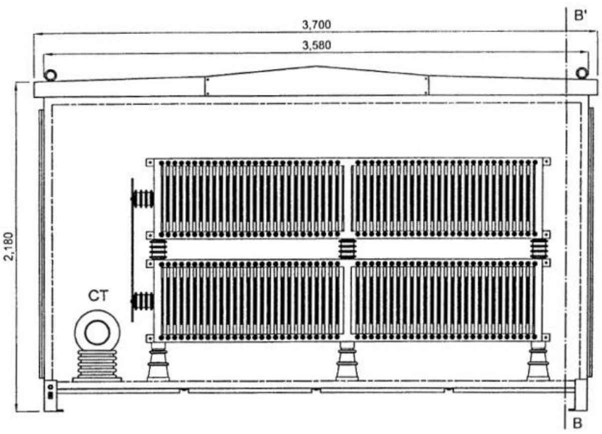
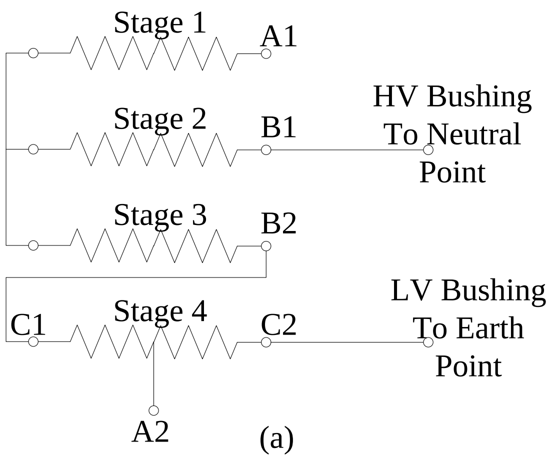


Fig. 2: View of the NGR, the stages, and the CT



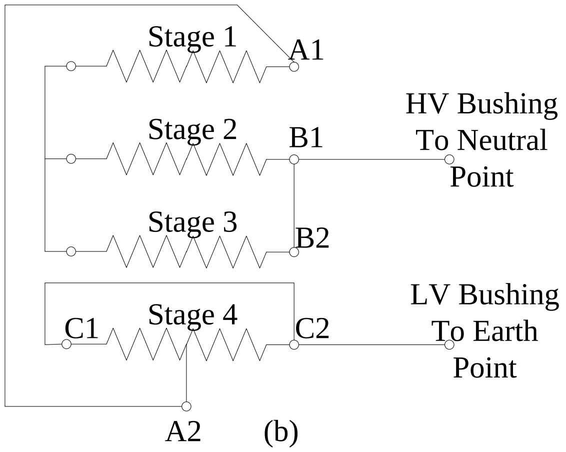


Fig.3. The connection configurations for (a) the 47.6 ohm and (b)127 ohm taps of the 11kV/33kV transformer NGR at The Fourth Refinery

B. Single phase to ground short circuit at the connection line to phases 2 and 3

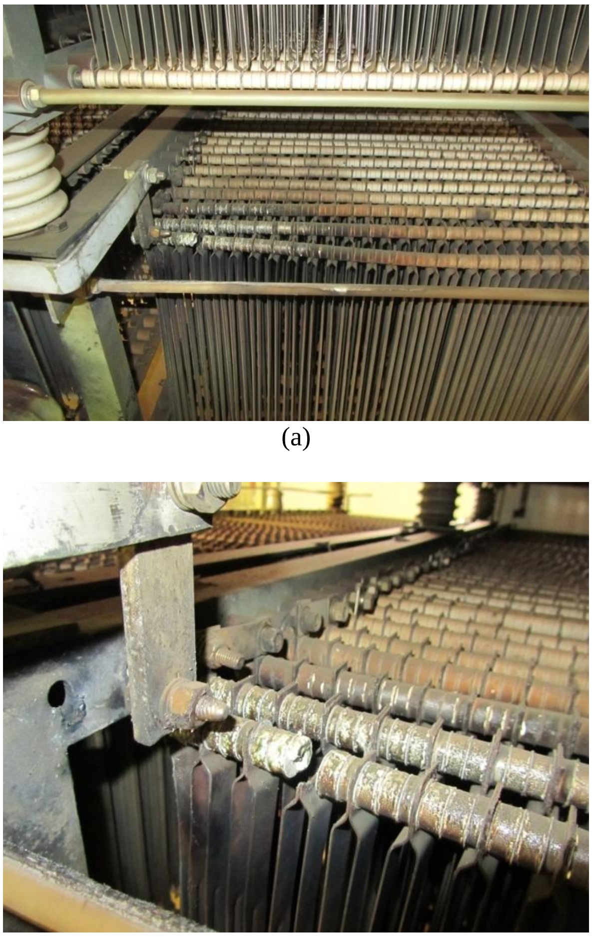
This accident occurred on Jan. 3, 2011. At the time of the accident, gas turbines 1, 3, and 4 were in operation. The Fourth Refinery was consuming 23 MW and Refinery No. 2 was consuming the 23 MW backup power supplied for Refinery 4. The fault occurred at the cable head of the junction connecting the overhead lines to the underground cables (providing backup power to phases 2 and 3 from phases 6, 7, and 8) between Phase 1 corridor and Phase 2.

C. Single Phase to Ground Short Circuit at the Input to Station No. 13

Before this accident which occurred on Jan. 20, 2011, the refinery was working normally, being supplied via Mobin Power Plant and turbine Generator No. 1 (connected synchronously). The refinery was receiving 25 Mw of power. This single phase to ground fault at the power transmission line of Transformer 13TR1 (power transmission line from Power Station No. 4 of the refinery to the power station at the catchment area) disconnected the circuit breaker, the input A/B switches, and all the relays and feeders at the output of Sub1 in the refinery, causing a severe drop in the power plant load, followed by an “out of service” position in the power plant and an “emergency stop” position for all the process and utility units.

IV. Description of the Faulty NGRs

During the visits to the site where the faults had occurred, we found that the insulators supporting the ribbon resistors as well as the resistors themselves had broken (Fig. 4). At some points, the electrical connection had been cut off and at a significant number of other points, the ribbon resistors had been separated, leading to NGR open circuits. In many parts, the failure was accompanied with sparks. This indicted that some NGR points had been exposed to transient over voltages. On the other hand, as the supporting rod of the resistors and even the ribbon resistors had melted, we concluded that the NGR had been subjected to current stresses and that the resistors could not withstand the passing current resulting from the short circuit. These points are unclear since there is not enough information regarding the failure of the NGRs.



(a)

(b)

Fig. 4: The damaged NGRs (a) failure of the ribbon resistors and (b)their supporting insulators

There is no information regarding the exact time of these NGR failures. The reason is that the NGRs were not constantly monitored at the time; therefore, it was not possible to determine the very event (from among the events referred to in Section 4.3) which the failure coincided with. The only available information was the dates on which the PM personnel discovered the NGR failures during their routine inspections and consequently transferred them to the workshop for repairs. These transfer dates are as follows:

A. 15-TR-4 : Jan. 28, 2012
B. 15-TR-3 : Feb. 26, 2012
C. 15-TR-1 : March 01, 2012
D. 15-TR-1 : June. 05, 2013

V. Charging Current Calculation

Capacitance between one phase and earth, defines network charging current[2] .For each of equipment, charging current calculated and summation of them is total network charging current. In this section, we calculated Fourth Refinery network charging current

A. The 33 kV Cables

The charging current for transformers is about 0.05 A/MVA[3]. The total transformer capacities at The Fourth Refinery are presented in Table 1.

Table 1: Transformers installed in The Fourth Refinery

Transformer	Capacity
132kV/33kV	100 MVA
33kV/6.3kV	224.8 MVA
33kV/4.2kV	44.1 MVA
11kV/33kV	230 MVA

Thus, the total charging current for all the transformers is:

$$0.05 * 599 = 29.95 \quad (1)$$

B. The 33 kV Cables

The charging current for the 33kV cables is calculated from the following relation [4]:

$$C = \frac{\varepsilon_r}{18 * \log_{10}\left(\frac{D}{d}\right)} \quad (2)$$

Where C is the capacitance to ground (μF/km), D is the diameter of cable insulation (mm), d is the diameter of the conductor (mm), and εr is the dielectric permittivity coefficient.

Table 2 lists the sizes and lengths of the 33kV cables in The Fourth Refinery.

Table 2: The 33 kV Cable charging currents

Charging Current (A)	Y=WC (mho)	Capacitance (μF/km)	Length (m)	Cable (Cu/XLPE)
61.73	0.00108	0.18	19130	3(1*120)
19.976	0.0003495	0.228	4880	3(1*240)
15.66	0.000274	0.252	3460	3(1*300)
17.1	0.000299	0.275	3460	3(1*400)
79.22	0.001386	0.336	12130	3(1*630)

Therefore, the charging current of the 33kV cable is obtained as:

$$3I_{C0} = 193.686A \quad (3)$$

C. Total Charging Current

The total charging current at The Fourth Refinery was obtained as:

$$3I_{C0} = 29.95 + 193.686 = 223.636A \quad (4)$$

D. Maximum and Minimum Charging Currents in 33 kV Feeders

The current passing through an NGR under fault conditions must be greater than the maximum charging current of the feeders[4]. According to the standard current ranges, a current value of 400A is selected. A protective earth fault relay must be adjusted so that it can pass a greater current than the charging current of fault-free feeders. The current adjustment for this relay must be 10% of the maximum current under short circuit conditions.

VI. Simulation

A. Modeling of the Network

To investigate the dynamic state of the power plant network system in the refinery before and during the fault, we used the recorded information and MATLAB to simulate the conditions with due regard to the following: the generators that were in operation when the accidents occurred, the reports presented in Section 1.2 regarding the active load at the instant the fault occurred, power delivery of each generator, power delivery of Mobin Power Plant, and power delivery of Phases 2 and 3 to the Fourth Refinery network. First, the network (grid) was simulated under normal conditions to investigate the state of unbalanced forces, harmonics, resonance, etc. Then, the information provided in the reports was used to apply a single phase short circuit to the system and study the NGR behavior during and after the short circuit.

NGR failure occurs in two ways: 1) the NGR is disconnected, or 2) the NGR is partially short circuited. As both these cases entail certain risks[1],[5], they are also included in short circuit simulations.

B. The NGR Model

In this section, all the components of the NGR were simulated so that the stresses thereof can be determined. Subsequently, all the stages, the resistor elements, and the ribbon resistors were simulated. Fig. 5 shows the simulation block corresponding to an NGR.

Fig. 6 shows the simulation blocks corresponding to various NGR stages with a 47.5 ohm tap. Stage No. 1 had a resistance of 15.75 ohms, and the resistance of the other stages (2, 3, and 4) was 42.3 ohm.

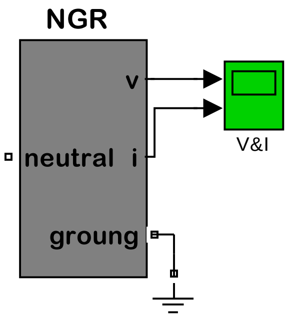


Fig. 5: The NGR simulated block

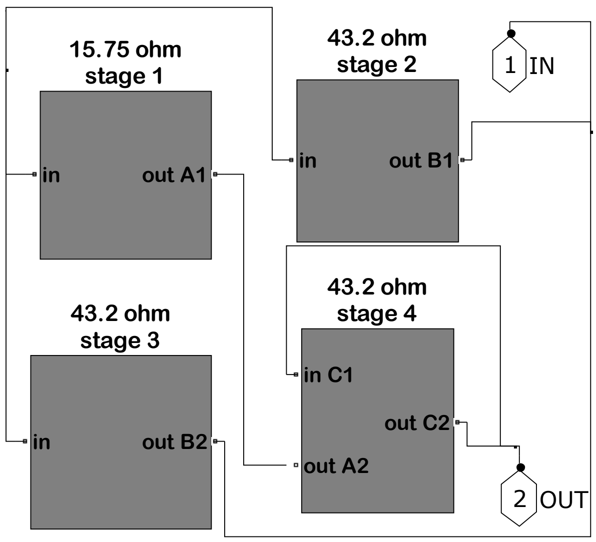


Fig.6. NGR simulation of the 47.5 ohm tap connection(see Fig.3)

VII. Simulation Results

A. Simulation Results under Normal Operating Conditions

Fig. 7 shows line voltages and currents at Bus A, Station No. 1 under normal operating conditions. Fig. 8 shows the NGR voltage and current obtained for 15TR1 under normal conditions for the case when this transformer was the only transformer in operation in the circuit. As can be observed from these results, the voltages and currents at Bus A were well balanced. The same was true for all the other electric buses.

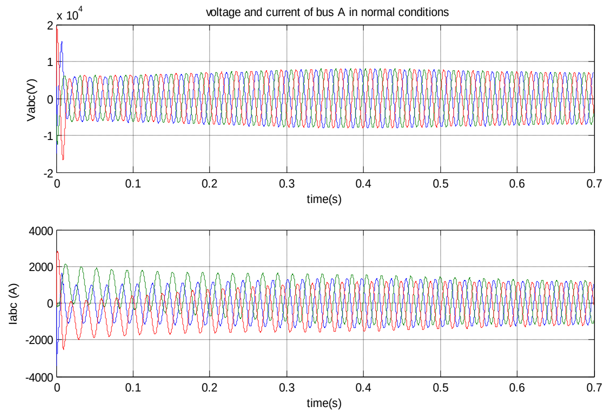


Fig.7. Line voltages and currents obtained for Station 1 of Bus A under normal working conditions

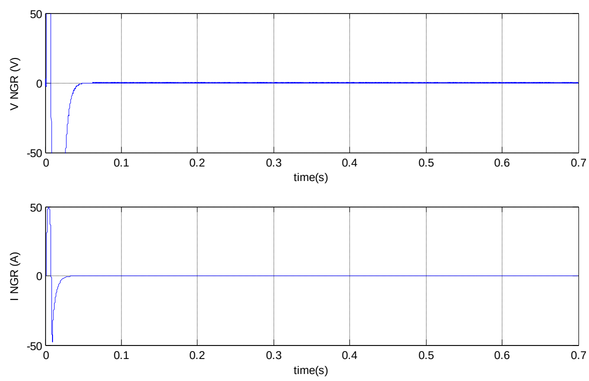


Fig.8. NGR voltage and current for 15TR1 under normal working conditions

Percentage voltage harmonics in Bus A are shown in Fig. 9 (THD=4.3%). Fig. 10 shows the current percentage harmonics for Bus A (THD=7.65%). These are also in the normal range.

Fig. 8 demonstrates that the voltage across the NGR is almost zero. This is also the case for the NGR current.

B. Simulation Results for to Ground Short Circuit at Bus A (The Catchment Area Station Accident)

The line voltage and current results obtained upon applying a single phase short circuit at Bus A are presented in Fig. 11. In this case, the single phase short circuit was applied for 0.3 s and was over in 0.8 s. As can be seen, the grounded phase voltage changes to zero and the other two phase voltages were increased by SQR(3). The grounded phase current was also increased.

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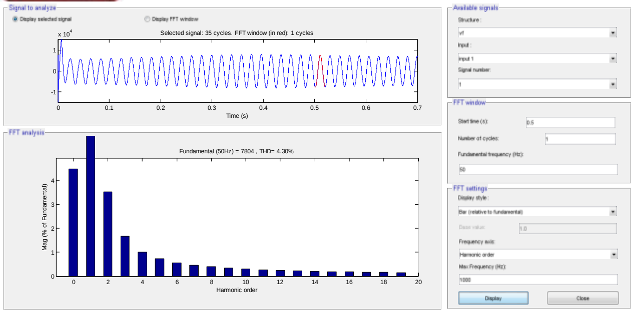


Fig.9. Percentage voltage harmonics for Station 1 of Bus A under normal working conditions

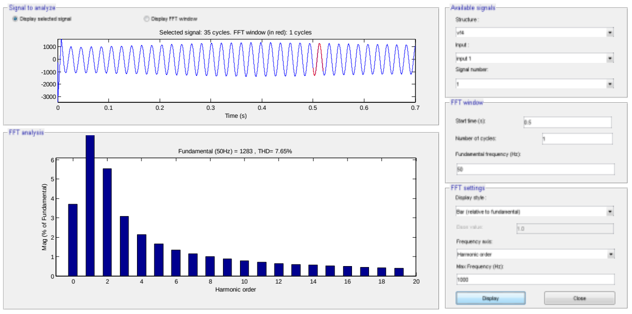


Fig.10. Percentage voltage harmonics for Station 1 of Bus A under normal working conditions

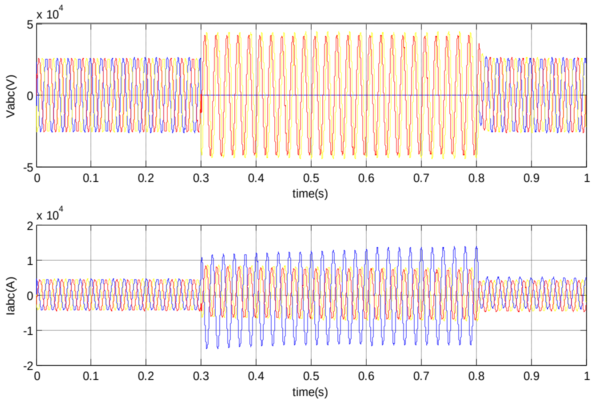


Fig. 11: Line voltages and currents obtained for Station No. 1 of Bus A under single-phase ground short circuit

In the second step, the effects of open circuit or partial short circuit conditions at the NGR under short circuit conditions were studied.

C. Simulation Results for Open Circuiting of NGR during Single Phase to Ground Short Circuit

It was assumed in the simulation that at t=0.6 s, i.e., 0.3 seconds after applying the single phase to ground short circuit, the NGR is accidentally open circuited. It was also assumed that the short circuit ended at t=0.8 s. We open circuited the NGR at points A1 and A2 during simulation. Fig. 12 shows line voltages and currents of Bus A at Station No. 1. Fig. 13 shows the NGR voltage and current obtained for 15TR1 under single phase to ground short circuit conditions in the case when the NGR is open circuited during the short circuit. As can be seen, the voltage waveform did not change upon NGR's being open circuited. The current waveform amplitude decreased slightly as compared with the short circuited current. However, this was negligible since the short circuit current would pass through the Mobin Power Plant NGR any way.

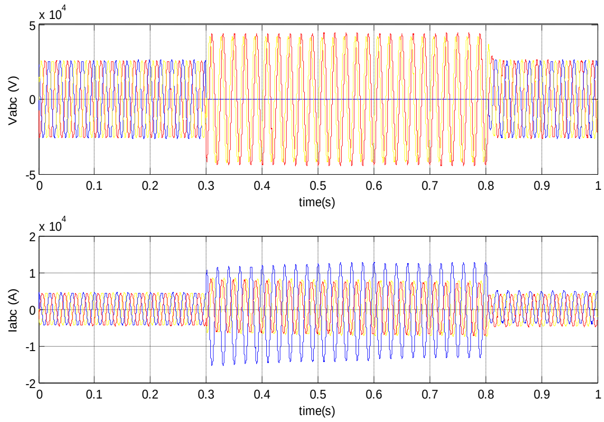


Fig.12. Line voltages and currents for Station No. 1 of Bus A under single-phase ground short circuit occurring at Bus A due to disconnecting the NGR

Fig. 13 shows that at t=0.3 s when the fault occurs, the NGR voltage increases by approximately 19 kV, causing a 400 A current to pass through the same. Then, at t=0.6 s when the NGR is accidentally open circuited, over voltage and electric arcs were experienced by the NGR followed by sparks on the NGR and its body. It is possible that the insulators and the dielectric materials used for isolating the NGR electrically were unable to withstand this overvoltage. After this,, the current passing through the NGR dropped to zero as expected.

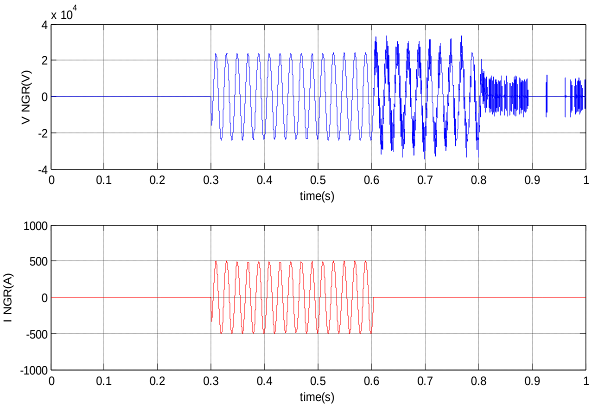


Fig.13. NGR voltage and current obtained for 15TR1 under single-phase ground short circuit in the case of NGR disconnection during fault conditions

Fig. 14 shows the NGR voltage between A1 and C1 under single phase to ground short circuit when the NGR is open circuited during the fault. As can be seen, occurrence of the fault at t=0.3 s established a 3.5 kV voltage across the NGR. At t=0.6 s, the NGR was open circuited, and consequently, a 21 kV overvoltage was experienced by the NGR. Obviously, the dielectric gaps are unable to withstand such an overvoltage t A1 and C1. Thus, most failures must have occurred at Stage 4. This overvoltage remained at the neutral point of the system even after the short circuit to ground fault was removed due to the NGR's being open circuited.

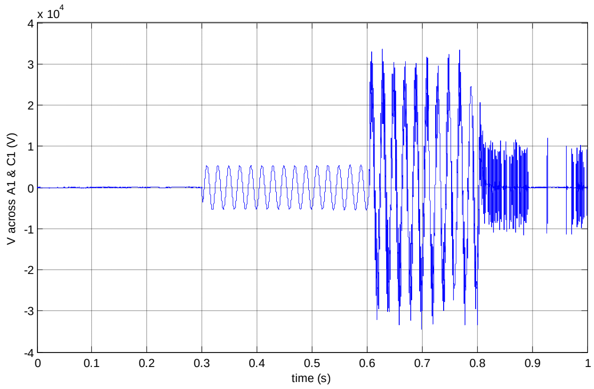


Fig.14. NGR voltage between points A1 and C1 under single-phase ground short circuit in the case of NGR disconnection during fault conditions

D. *Simulation Results for Partial NGR Short Circuit during Single Phase to Ground Short Circuit*

It was assumed in this simulation that 0.3 seconds after the application of single phase to ground short circuit, i.e., at t=0.6 s, the NGR was partially short circuited as a result of an accident, and that this short circuit was removed at t=0.8 s. The accidental short circuit was applied between points "in" and C2.

Fig. 15 shows the NGR voltage and current at 15TR1 under single phase to ground short circuit conditions for the case where the NGR is accidentally short circuited during the fault (i.e., a part of resistors are excluded from the circuit). No change can be observed in the NGR voltage waveform after the short circuit. However, regarding the current waveform, as seen from the figure, the constant voltage across the NGR is doubled due to the partial exclusion of the resistors from the circuit. The ribbon resistors cannot withstand this double current and burn as a result.

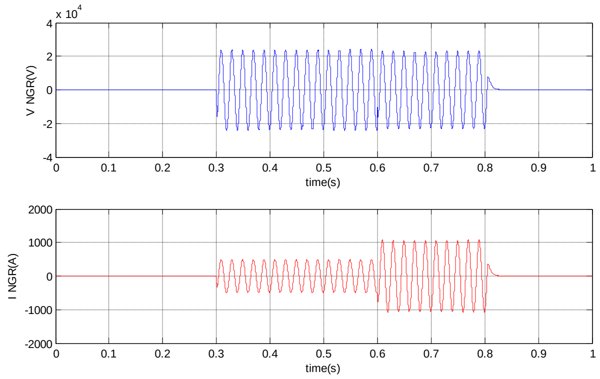


Fig.15. NGR voltage and current for 15TR1 under single-phase ground short circuit in the case of partial NGR disconnection during fault conditions

VIII. PRACTICAL TESTS

A. *Thermography Tests*

Fig. 16 shows the thermography test results at points a and b. This test was conducted on a transformer NGR at the power plant under normal operating conditions. As can be observed from the figure, maximum temperature occurs at Point a (70.1 C). This is within the allowable temperature range as designated in the IEEE32 standard.

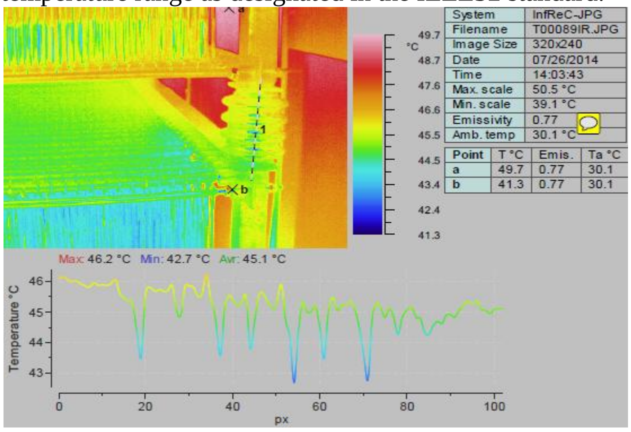
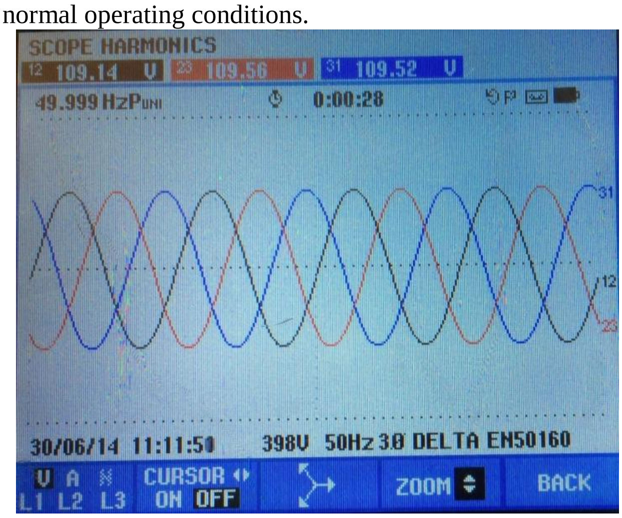


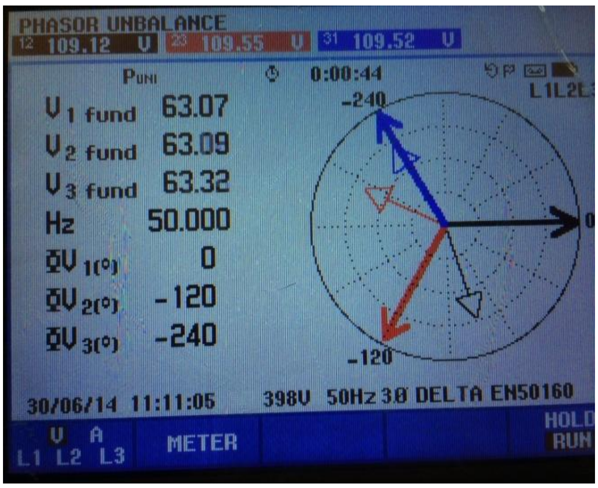
Fig.16. Thermography results at points a and b

B. *Voltage Balance Test*

This test was conducted on the Power Station 1 buses using a power analyzer. The results are shown in Fig. 17. As can be seen, the phase voltages are balanced under normal operating conditions.



(a)



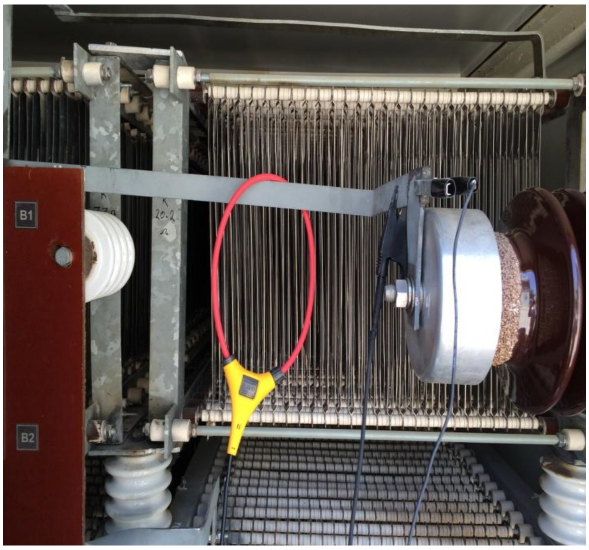
(b)

Fig.17. Voltage balance test conducted on the buses of Station No. 1 in the refinery (a) Voltage waveform (b) vector diagram

C. The Harmonics Test

This test was conducted on the NGR using a power analyzer. The wiring method used in this test for connecting the NGR to the system is shown in Fig. 18.

(a)



(b)

Fig.17. NGR power analyzer wiring for conducting the harmonic test

The following procedure was followed in the harmonics test: One out of service generator at the power plant was loaded in 2 MW steps up to 10 MW, and at each step, the NGR voltage and current were recorded (Table 3). At each step, the current harmonics were also measured. The current harmonics obtained for the first step are shown in Fig. 19 where the black strips are due to the measuring channel. Note that this test was conducted on a generator which was in synchronous operation with Mobin Power Plant. The results showed that the current harmonics are in the allowable range. It was, therefore, concluded according to [6] that the problem has not been caused by the interfering harmonics resulting from the generator's being in synchronous operation with Mobin Power Plant.

Table 3: Voltages and currents measured for NGR

Power	Voltage	Current
2MW	2.67	57mA
4MW	2.6	55mA
6MW	2.5	53mA
8MW	2.43	52mA
10MW	2.39	51mA

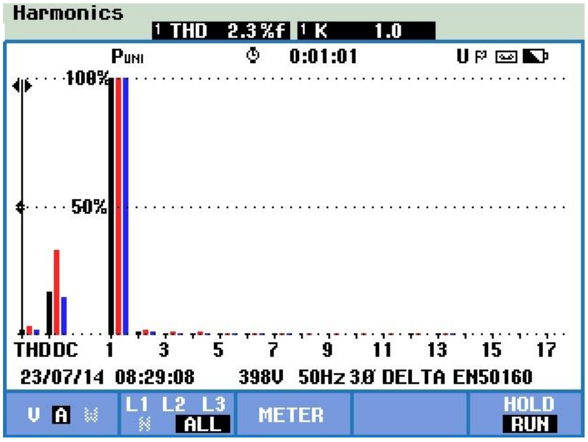


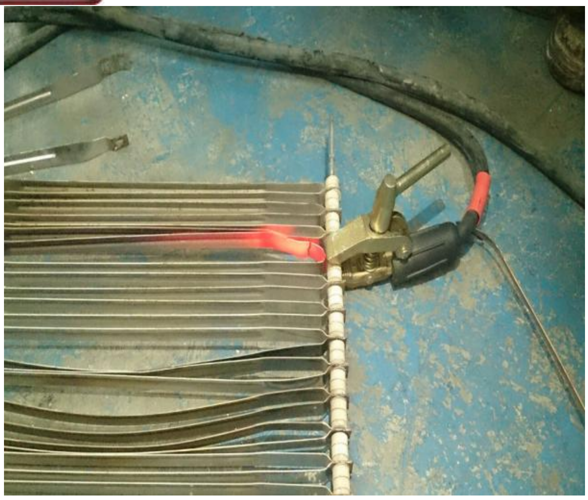
Fig.19. Percentage harmonics: NGR current for 15TR1 at the first step (2MW) under normal working conditions

D. Current Test of the Spot Welds

Since the ribbon resistors had been spot-welded in series, it was necessary to conduct the current test on the NGR ribbon resistors. The spot welds current test is similar to the rated current test where the rated current of each stage is passed through the ribbon resistors of the same stage to determine whether the spot welds and ribbon resistors can withstand this current during a single phase to ground short circuit. We first conducted this test on the ribbon resistors of Stage No. 4 since this stage had received the greatest share of the damage incurred.

Upon establishing the rated current across Stage No. 4, the ribbon resistors of this stage failed within 10 seconds. Fig. 20 shows the results of this test. Therefore, the ribbon resistors could not withstand the rated current and failed, thus open circuiting the NGR.

(a)



(b)

Fig. 20: Rated current test conducted on each NGR stage (a) resistors could not withstand the rated current (b) open circuiting the NGR

IX. Conclusion

The results obtained in this study can be used as an authentic source for conducting further development studies on power plant stations in gas refineries as well as petrochemical and transmission stations.

Moreover, by implementing the relevant IEEE standards and other reliable sources in examining the NGR faults at The Fourth Refinery, the results of such studies can be used as a reliable document for detecting NGR faults (at both low and high resistance) at all power plant stations in order to prevent stoppage and ensure continuous operation.

In this study, the section related to NGR Tests in IEEE32 standard (including the Temperature Rise Test, the HIPOT Test, the Rated Current Test, and the Spot Weld Test) was studied. On the other hand, through simulation of The Fourth Refinery and examining the single phase to ground short circuit case (similar to that reported in the accident reports), all the possible cases were duly investigated.

The spot welds test revealed that the NGR had failed in less than 0.6 s, so that it could not withstand its own rated current. It was therefore concluded that the failure of the NGRs

Was due primarily to the excessive heat resulting from the over current (this was also observed in the defective NGRs). The results of the NGR open circuiting during single phase to ground short circuit showed that an over voltage of 6 times the rated voltage had occurred at the same stages, leading to an electric arc. In practice, this over voltage caused electric arcs accompanied by strong sparks which the dielectric gaps were unable to withstand. These over voltages remained at the neutral point within the system as a result of the NGR being disconnected from the circuit (open circuit condition).

Therefore, with due regard to the results obtained from the practical tests and simulations, we can reach the following conclusion: As the result of single phase to ground short circuit, those ribbon resistors which could not withstand the short circuited current passing through NGRs began melting and consequently failed. Then, as the NGR was open circuited, the over voltage and the consequences thereof, namely, the electric arc and strong sparks, were observed.

The same has happened in all the transformer NGRs at the power plant. The simulation results revealed that the most damage occurred at Stage 4. This result was confirmed by actual filed evidence.

The authors recommend that the following measures be taken:

1. Installing a monitoring system: We have attempted in this research to build an economical color display with the least wiring and modification, capable of monitoring the required processes.
2. Replacing unit taps each time a unit enters or exits the power plant: This is necessary because if the taps are not replaced at each entry or exit, the unit's earth connection system is turned into either a high resistance or a low resistance system.
3. Changing the material and type of the NGR resistors. We propose that the present "stamped ribbon resistors" be substituted with "stamped grid resistors".

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

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